News on the s process from Young Open Clusters

Enrico Maiorca[1,2,3], Laura Magrini[2], Maurizio Busso[1,3], Sofia Randich[2], Sara Palmerini[1,3],

Oscar Trippella[1,4]

[1]Department of Physics, University of Perugia, Via Pascoli, 06122, Perugia, Italy; emaiorca@gmail.com

[2]INAF, Osservatorio Astrofisico di Arcetri, Largo Enrico Fermi 5, 50125, Firenze, Italy

[3]INFN, Section of Perugia, Via Pascoli, 06122, Perugia, Italy

[4]INFN, Laboratori Nazionali del Sud, Via Santa Sofia, Catania

ABSTRACT

Recent spectroscopic measurements in open clusters younger than the Sun, with [Fe/H] $\gtrsim 0$, showed that the abundances of neutron-rich elements have continued to increase in the Galaxy after the formation of the Sun, roughly maintaining a solar-like distribution. Such a trend requires neutron fluences larger than those so far assumed, as these last would have too few neutrons per iron seed. We suggest that the observed enhancements can be produced by nucleosynthesis in AGB stars of low mass ($M < 1.5 M_\odot$), if they release neutrons from the $^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}$ reaction in reservoirs larger by a factor of 4 than assumed in more massive AGBs ($M > 1.5 M_\odot$). Adopting such a stronger neutron source as a contributor to the abundances at the time of formation of the Sun, we show that this affects also the solar s-process distribution, so that its *main component* is well reproduced, without the need of assuming ad-hoc primary sources for the synthesis of s elements up to $A \sim 130$, contrary to suggestions from other works. The changes in the expected abundances that we find are primarily due to the following reasons. i) Enhancing the neutron source increases the efficiency of the s process, so that the ensuing stellar yields now mimic the solar distribution at a metallicity higher than before ([Fe/H]$\gtrsim -0.1$). ii) The age-metallicity relation is rather flat for several Gyr in that metallicity regime, so that those conditions remain stable and the enhanced nuclear yields, which are necessary to maintain a solar-like abundance pattern, can dominate the composition of the interstellar medium from which subsequent stars are formed.

Subject headings: Stars: evolution — Stars: AGB and post-AGB — Stars: Carbon — Stars: low-mass — Nuclear reactions, nucleosynthesis, abundances

1. Introduction

Very recently, measurements of s-process elements in young Galactic stellar systems (D'Orazi et al. 2009; Jacobson et al. 2011; Maiorca et al. 2011, hereafter Paper I) indicated that the neutron-rich nuclei Y, Zr, Ba, La and Ce are enhanced as compared to the Sun. The enhancement factor is $\simeq 0.2$ dex, and is the same (within uncertainties) for the heavier s elements (Ba, La Ce, hereafter hs) and for the lighter ones (Y, Zr, hereafter ls). Hence, a roughly solar ratio between the two groups is maintained[1].

The stellar systems involved are open clusters (hereafter OCs) younger than the Sun, belonging to the recent evolutionary stages of the Galactic thin disk. In the evolution of the disk, over several Gyr, the observed metallicity [Fe/H] ($\equiv \log (N(\mathrm{Fe})/N(\mathrm{H})) - \log (N(\mathrm{Fe})/N(\mathrm{H}))_\odot$) does not increase appreciably with time (rather, for every epoch the observations of [Fe/H] show a considerable scatter). These facts hamper the possibility of identifying definite trends in the abundances of heavy elements as a function of iron (Mashonkina & Gehren 2001; Mashonkina et al. 2007). In the case of open clusters, however, one has a reasonably good knowledge of their ages (see e.g. Magrini et al. 2009), so that using this information we could show the abundances of neutron-rich elements directly as a function of time. This was the key to reveal clearly the mentioned enhancement. (Previous studies on field stars had already tentatively suggested this as a potentially effective procedure, see Mashonkina & Gehren 2001).

Chemical and chemo-dynamical models of Galactic evolution (Travaglio et al. 1999, 2004; Raiteri et al. 1999), based on the currently-accepted scenario for s processing, predict a plateau, or even a decrease in the abundances $[X_i/\mathrm{Fe}]$ of neutron-rich elements after the

---

[1]The abundance of Sr, in general difficult to obtain, could not be measured because its useful lines were outside the wavelength range of the available spectra

solar formation; a late increase is certainly not expected.

The new results can be understood in either of two possible cases. The first possibility lays in the late emergence of a purely secondary-like neutron-capture process, i.e. one driven by a neutron source not synthesized by the star from pure H, but derived from elements inherited at stellar birth. The abundances of s elements thus produced would grow steadily in time as compared to iron, becoming appreciable only in advanced epochs. This would be the case for the $^{22}Ne(\alpha,n)^{25}Mg$ source, activated in Intermediate Mass Stars (IMS). ^{22}Ne is indeed produced by two α captures on ^{14}N, which in its turn derives from p-captures on the original CNO nuclei collected from the interstellar medium (ISM). However, the present knowledge of s processing in the Sun and in the Galaxy, and especially of the low neutron densities at which it must occur (Arlandini et al. 1999), excludes this possibility. Indeed, it would imply an isotope mix in the solar composition, for elements sensitive to reaction branchings along the s-process path, incompatible with meteoritic abundances (see e.g. Käppeler et al. 1990; Arlandini et al. 1999). It would also produce an insufficient number of neutrons to feed effectively the hs elements (Busso et al. 1988) and would fail to explain the observed abundance ratios among Sr, Y and Zr in carbon stars (Abia et al. 2001).

The only alternative is that the contribution from the $^{13}C(\alpha,n)^{16}O$ neutron source in low mass stars be larger than so far adopted in AGB models. In such a case, however, it is important to verify that any model change required to fit the OC data does not affect the many constraints on AGB nucleosynthesis that have already been accounted for (see e.g. Busso et al. 1999, 2001). In the present paper we aim at demonstrating that, for explaining the new observational evidence, it suffices that the ^{13}C reservoir be larger than previously assumed only in very low mass stars ($M < 1.5M_\odot$). This would not modify previous interpretations of s-enriched AGB stars in the solar neighborhoods, which have a higher mass (about 1.5 to $2.5M_\odot$, see e.g. Abia et al. 2002; Guandalini et al. 2006;

Guandalini & Busso 2008). It must be noted that the standard models used so far for them (as well as for the Sun) underproduce the light elements Sr, Y and Zr with respect to the solar abundances (see Travaglio et al. 2004, for details). We instead aim at showing that our assumptions have the further advantage of avoiding this problem, thus accounting completely for the solar *main component*, i.e. for the abundances of all s elements heavier than Kr-Rb.

This paper is organized as follows. In Section 2 we briefly discuss the changes necessary in the models in order to explain the new observational data and we outline our approach. In Section 3 we discuss the new stellar yields. In Section 4 we present our main results, and substantiate the claim that they also explain the solar s-process distribution. Then, in Section 5 we summarize our main conclusions.

2. Revised models for the s-element enrichment

In the current literature, one usually finds the same assumptions on the formation of the ^{13}C neutron source, for all LMS between 1 and $3M_\odot$. In particular, the mass of the layer where ^{13}C is formed (the so-called ^{13}C-*pocket*) is kept constant in most s-process nucleosynthesis models, while the average abundance by mass of ^{13}C inside the pocket is parameterized, to give sufficient neutrons to reproduce the observed constraints. (One has actually to recall that there is no ab-initio physical model for the formation of this neutron source, but the observational data require s processing from its activation in AGB stars, as discussed, e.g., by Gallino et al. 1998).

Recently, looking for a better physically-justified scenario, the proton penetration into the intershell zone was assumed to be the consequence of a naturally-decaying velocity profile of the convective eddies at the envelope border (Straniero et al. 2006, 2009;

Cristallo et al. 2009). This decay was regulated by a free parameter (β), but again a unique value ($\beta \sim 0.1$) was derived for it, independently on the stellar mass (see e.g. Straniero et al. 2006).

There is ample space to revise the above assumptions in the attempt to explain the s-process abundances in OCs; however, as mentioned, the revisions must preserve the interpretation of the abundances in s-process-enriched AGB stars, which have already been successfully achieved (Busso et al. 2001; Abia et al. 2002). As these last are known to have masses $M \gtrsim 1.5 \ M_\odot$, we have a large freedom in choosing the parameters for the ^{13}C pocket in stellar masses lower than this limit. If born today (at solar or higher-than-solar metallicity) such low mass stars would barely activate, during the AGB stages, the third dredge-up (TDU) necessary to carry He-burning products to the surface. However, the efficiency of TDU rapidly increases for decreasing metallicity, so that at progressively lower values of [Fe/H] we expect that stars of progressively lower mass can contribute (albeit with a limited number of pulses and TDU episodes). One of the scopes of this paper is to explore their impact on the Galactic chemical evolution, especially for the recent epochs in which OCs were formed.

We take general predictions for mass loss rates, TDU efficiency and total number of pulses from the work by Straniero et al. (2003). This paper provides us with the general stellar parameters, which have been often used in works where a global picture of AGB nucleosynthesis was needed, like e.g. Wasserburg et al. (2006). The stellar models described in Straniero et al. (2003) are also the same used in previous Galactic chemical evolution calculations for the s process (Travaglio et al. 1999, 2004). By adopting them we can verify the effects introduced exclusively by the new proposal here advanced.

In the present work, we have modeled the formation of the ^{13}C pocket, for stellar masses below $1.5 M_\odot$, by assuming that hydrogen can be injected into the He-rich layers at

TDU. The abundance of protons X_H is assumed to exponentially decrease for increasing depth (in mass) into the He zone. The maximum depth reached was set to $4\times10^{-3}M_\odot$, i.e. 4 times larger than currently assumed (cf Gallino et al. 1998). At the restart of shell-H burning, the upper part of this region becomes enriched in ^{14}N, a strong neutron filter hampering s-processing. The effective zone where the nitrogen competition is negligible turns out to correspond to a total mass of ^{13}C available for s-element production $M_{13} = 1.2 - 2 \times 10^{-5}M_\odot$ (depending on the details of the proton profile assumed). This means that, over the depth of the pocket ($4\times10^{-3}M_\odot$), we have an average *effective* abundance by mass, $\bar{X}_{13}$, in the range $\simeq 3 - 5 \times 10^{-3}$. For more massive AGB stars, assumptions very similar to those discussed by Travaglio et al. (2004) were instead maintained, with an average mass of ^{13}C burnt per cycle of $3.1\times10^{-6}M_\odot$.

With the above prescriptions we computed the s-process *yields* (i.e. the contributions in solar masses from the AGB stellar winds to the ISM). The set of neutron-capture cross sections and of other nuclear inputs was taken from the KADONIS database and from the further recent improvements; see e.g. Käppeler et al. (2011) for a general discussion.

Our stellar yields were then introduced into an improved version of the Arcetri Galactic chemical evolution model, which is very similar to the code used and updated by Travaglio et al. (1999, 2004). For the present work we have considerably improved the code. This revision included: i) adopting a fine mass resolution ($0.05M_\odot$) for the contributing AGB stars in the range of interest ($1.25\lesssim M \lesssim 1.5M_\odot$); ii) using a detailed dependence on metallicity of the stellar yields (providing them at seven different values of [Fe/H]); and iii) estimating the Galactic enrichment using relatively small time steps (25 Myr), in order to better describe the final phases of the Galactic chemical enrichment. In particular, sampling properly the change of the stellar yields with metallicity is of paramount importance; in many previous models the stellar contributions were estimated at few metallicity values

(sometimes only two), but such a course grid is not adequate for following s-element abundances. This is clear, e.g., from Busso et al. (1999), in particular their Figure 12, where it is shown how, for any choice of the ^{13}C neutron source, the stellar s-element yields do not increase monotonically with time and/or metallicity, so that their trends must be sampled carefully. Since s-processing is dominated by LMS contributors, also a high resolution in time and stellar mass is important, as for them a minimum variation in mass corresponds to large variations in the evolutionary lifetimes, τ_{ev}. These last were improved using the computations by Domínguez et al. (1999), which refer to the same FRANEC code from which the stellar evolution scenario is taken.

For the rest, the technique adopted and the main Galactic-model ingredients are very close to those of previous works on the subject, so that the results can be immediately compared with the ones by Travaglio et al. (1999, 2004). In this respect we have adopted, for the sake of consistency with previous works, the solar meteoritic abundances from the compilation by Anders & Grevesse (1989). On the other hand, for internal consistency, when referring to differential stellar data, we have used the solar photospheric abundances derived in Paper I for Y, Zr, La, and Ce and those from D'Orazi et al. (2009) for Ba. Those abundances are indeed on the same scale as those of open clusters, so that no systematic offset is introduced.

3.   The stellar yields

The yields coming from very low mass stars in the model proposed here are different than previously assumed, as the larger mass of the ^{13}C reservoir now adopted affects them strongly. The changes concern the total production factors in the winds and their trends with metallicity and time. A peculiar characteristic of the cases with a high ^{13}C mass to burn but with a small total stellar mass, hence a limited number of pulses, is that the

abundances in the He shell can be sampled by dredge-up before an asymptotic composition is reached in He layers. As a consequence, the s-element distribution carried to the surface changes greatly from pulse to pulse. In the first 3-4 TDU episodes mainly ls nuclei are contributed, while subsequently hs elements become more important. The final abundance pattern in the stellar wind is achieved through the averaging operated by convective mixing over the continuously changing composition that is dredged-up. In any case, no Population I AGB star with $M < 1.5 M_\odot$ is found to experience more than 10-11 TDU episodes (in accord with Bisterzo et al. 2010).

We note however that the predicted yields depend on the efficiency of dredge-up, which is an uncertain parameter of any model. In the parametrization by Straniero et al. (2003), eq. (3), it is presented as a function of the metallicity, of the H-exhausted mass (M_H) and of its increase during an interpulse period (δM_H). The values of these last two parameters depend crucially on the rates for H-burning reactions, and in particular on that for $^{14}N(p,\gamma)^{16}O$, the most critical one. The recent changes in the recommended value for this rate (Adelberger et al. 2011), not included in Straniero et al. (2003), certainly affect the TDU scenario: in particular, small variations in M_H and δM_H easily lead to a change in the minimum stellar mass contributing at Galactic disk metallicities, moving it inside the range $1.25 - 1.35 M_\odot$. Important effects on the amount of dredge-up are also induced by the set of opacities used and by the treatment of convection (see e.g. Cristallo et al. 2009). These are the most typical uncertainties that affect today the AGB inputs to Galactic chemical evolution models of s elements. As a consequence, all results must be taken with some caution; they can only provide a general guidance and not precise quantitative conclusions.
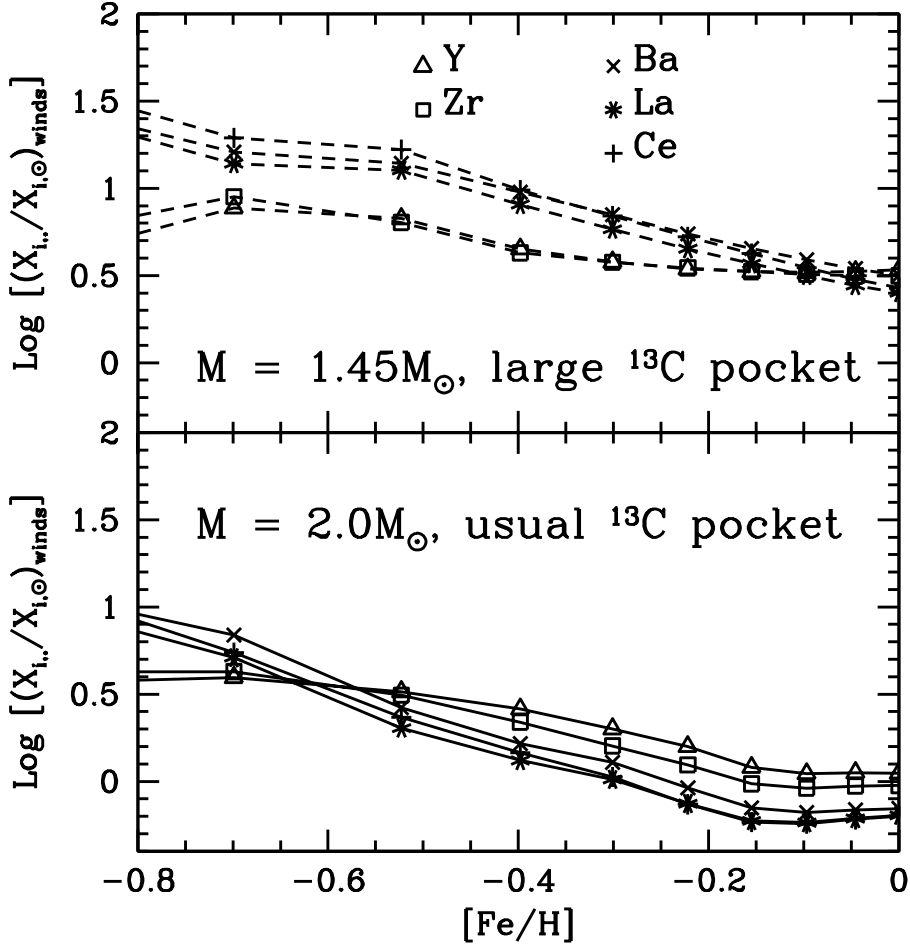
Fig. 1.— *Upper panel*: The s element contributions from a stellar mass below $1.5M_\odot$, expressed as production factors in the stellar winds with respect to the solar composition, adopting the extended ^{13}C pocket described in the text. *Lower panel*: the same contributions as obtained for higher masses with a standard ^{13}C pocket.

3.1. Stellar yields as a function of [Fe/H]

For values of [Fe/H] relevant for the Galactic disk, our typical yields are shown in Figure 1. The upper panel refers to our new assumptions on the ^{13}C pocket for very low masses ($M < 1.5M_\odot$), using a ^{13}C abundance $X_{13} = 4 \times 10^{-3}$. For comparison, the lower

panel shows the yields for stars with $M \gtrsim 1.5 M_{\odot}$, which are obtained with the older scenario and the older (smaller) choice for ^{13}C mass burnt per cycle. The upper panel, in particular, shows the situation for stars between 1.4 and $1.5 M_{\odot}$, which still have a rather efficient dredge-up for metallicities up to the solar one. It shows that the stellar wind composition, with the new ^{13}C pocket, is characterized by similar production factors for hs and ls elements (as compared to the solar distribution) only at a relatively high metallicity ([Fe/H] $\gtrsim -0.2$). At lower [Fe/H] values the hs are more effectively produced. The distribution is remarkably different than obtained for higher masses (lower panel). This is so both for the absolute values and for the $[hs/ls]$ ratios. In particular, the absolute yields at high metallicities remain high *only* for lower mass stars, with the larger ^{13}C pocket, while they are essentially negligible for higher masses, with the smaller, normally assumed ^{13}C reservoir.

The relevance of the trends shown in Figure 1 can be understood with reference to the age-metallicity relation of our model, illustrated in Figure 2. It is derived a priori, from the reproduction of the main species, like oxygen, the α-rich elements and iron and its behavior is typical in all modern Galactic evolution models. For our purposes, Figure 2 shows two important things: i) the SFR has remained rather high throughout the last 10 Gyr, after its peak in earlier epochs; ii) during the last 7.5 Gyr of the Galactic history the metallicity [Fe/H] has grown very little: over this whole, long era, it has remained within $\pm$ 0.2 dex from solar. When considered together, Figures 1 and 2 tell us that most of the stars in the Galactic disk were born with high metallicity; moreover, those having mass below $1.5 M_{\odot}$ (dominating the Initial Mass Function) generated, in their AGB phases, s-process yields close to those at the extreme right of Figure 1 (upper panel). The larger yields characterizing lower metallicity stars in Figure 1, with element ratios very far from the solar distribution, played only a marginal role in setting the composition of recent Galactic stellar systems, because too few stars were born in those conditions. These few

stars could synthesize effectively only elements whose overabundances in the stellar winds were extremely high. It is known that this is the case with lead, for which low-metallicity AGB stars provide the so-called *strong* s-process component (Gallino et al. 1998), producing about 50% of ^{208}Pb.
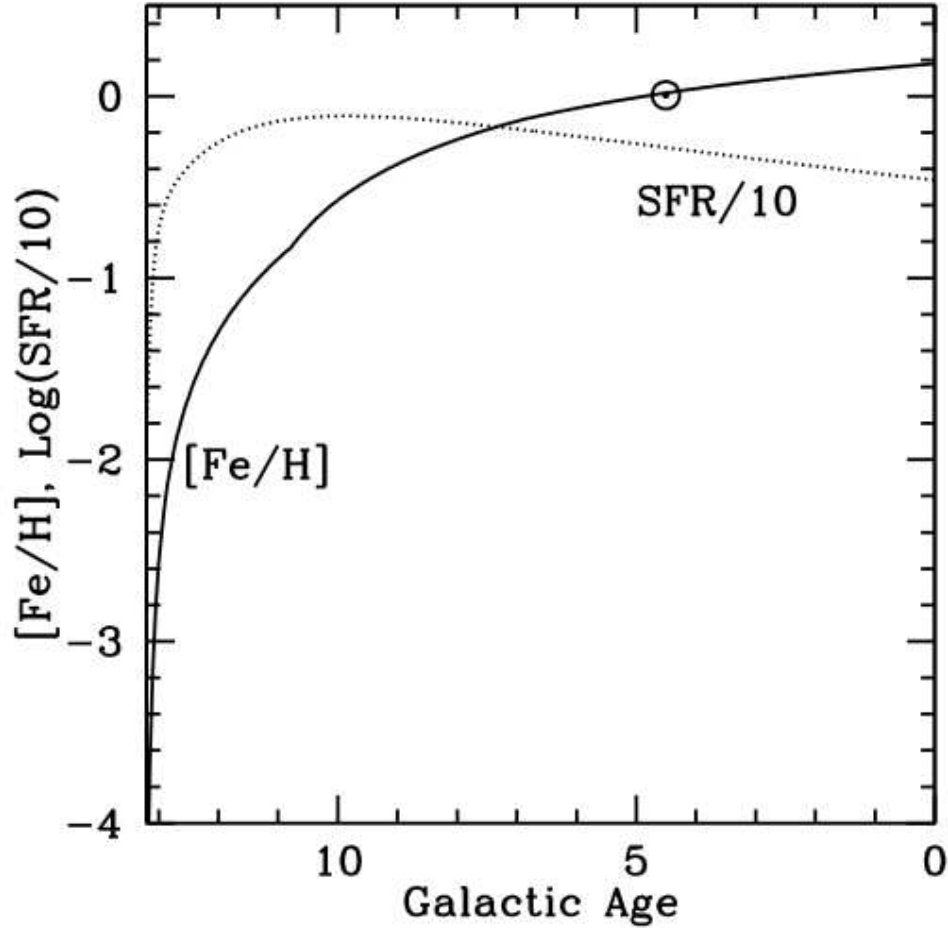

Fig. 2.— The continuous curve shows the age-metallicity relation obtained by our model, i.e. the history of the iron increase in time produced by the Galactic evolution calculation. The dotted line reports the Star Formation Rate (SFR), i.e. the mass going into stars over the whole Galactic disk at each epoch, in units of $M_\odot$/yr. The values of this function are divided by a factor of ten, in order to fit it in the ordinate scale.

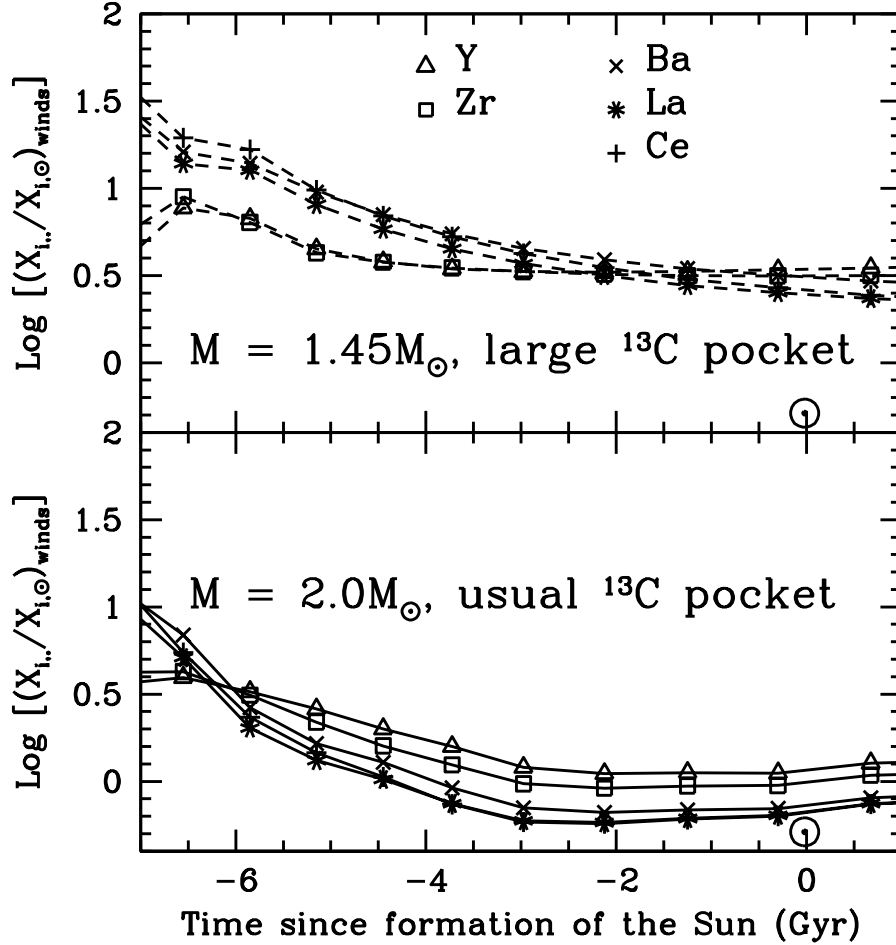## 3.2.   The Stellar yields as a function of time

Fig. 3.— The same enhancement factors in the stellar winds shown in Figure 1, plotted as a function time. The zero of the scale indicates the formation of the Sun. *Upper panel*: during more than 3 Gyr, before the solar formation, the production factors of s elements in the winds of very low-mass AGB stars have remained very similar. *Lower panel*: more massive stars, with a smaller ^{13}C pocket, could not play a significant role at high metallicities, because of their negligible yields.

In order to make the above statements clearer we can actually transform Figure 1 into

a plot as a function of time, using the age-metallicity relation of Figure 2 and setting the zero of the scale at the moment of the solar formation. This plot is presented in Figure 3. As one can see, the small region at the right side of Figure 1 (for [Fe/H] values larger than about -0.2), where the yields of ls and hs nuclei are about similar (within 0.2 dex), is now shown to start typically 3 Gyr before the solar formation. According to Domínguez et al. (1999), such an interval allows for the complete evolution of stars in the range $1.4 - 1.5 M_\odot$, whose lifetime, in this metallicity interval, ranges from 2.5 to 3 Gyr. As mentioned, at the relevant [Fe/H] values these stars did have TDU; hence they could affect the composition of the Sun and of stars born subsequently with about equal production factors for ls and hs elements, thus clarifying how these two groups of nuclei can increase their abundances in OCs, while maintaining their ratios relatively constant. We emphasize that, as Figures 1 and 3 show, at the times and metallicities mentioned, more massive stars had essentially no role on s-processing, because their yields were far too low.

The above figures make clear why the role of LMS in the chemical evolution of s elements can change remarkably relative to previous estimates, if a more extended ^{13}C pocket is assumed.

3.3. The yields of a typical single AGB model

The ls and hs contributions to the Galactic enrichment derive obviously from many stars of different mass and metallicity. Nevertheless, we can identify a typical s-element nucleosynthesis progenitor, providing yields for ls and hs elements whose mutual ratios are very close to those of the subsequent Galactic average (and of the solar distribution). With our large ^{13}C pocket, this turns out to be an AGB star of $1.4-1.45 M_\odot$, with [Fe/H] ~ -0.1. By normalizing to the abundances of s-only nuclei produced by such a model star, we can infer s-process percentages in its winds for the elements analyzed here. Using this estimate

for explaining the solar abundances we obtain 86%, 84%, 80%, 85%, 70% and 76%, for Sr, Y, Zr, Ba, La and Ce, respectively (see also later, Table 1). From this, assuming that the complement to one of the percentage abundances of the heavier elements (Ba, La and Ce) derives from the r process, we infer r-process components of 15%, 30% and 24% for Ba, La and Ce, respectively. These estimates are slightly higher than those by Bisterzo et al. (2010).

We now present the results on the abundance evolution of open clusters induced by our new hypotheses and then briefly discuss the consequences for the solar distribution.

4. The resulting s-process composition of the Galactic disk

4.1. Interpreting the observations of open clusters

In order to compute model expectations for the heavy elements in OCs we must necessarily include in the calculations estimates for their production in other astrophysical environments, outside the range of LMS to which our models refer. As already mentioned in Subsection 3.3, for Ba, La and Ce one can infer a rough estimate for their r-process contributions from the yields of our model star best reproducing the solar *main component.*

For lighter nuclei, the yields from IMS were estimated assuming that no ^{13}C burning occurs in them: the neutrons derive only from the activation of the ^{22}Ne$(\alpha,n)^{25}$Mg reaction in thermal pulses. They induce a secondary-like neutron-capture process, hence the yields vary as a function of the metallicity. The total IMS production of s elements is very uncertain, as these stars evolve almost entirely in the infrared during the thermally-pulsing phase, so that observational constraints are minimal and no trustable calibration of their mass loss rates, suitable for their use in stellar models, exists. As a consequence of this, the number of TDU episodes they undergo is unknown. While, from nucleosynthesis models in

thermal pulses, we can derive the s-element distributions in their winds pulse after pulse, not knowing the number of these last that can occur makes their global contribution to the chemical evolution of the Galaxy a rather free parameter, which must be calibrated ad-hoc. The ^{22}Ne$(\alpha,$n$)^{25}$Mg source is also activated during core-He and shell-C burning phases of massive stars (providing the so-called *weak component*, see e.g. Busso & Gallino 1985). For estimating the corresponding yields we modified previous estimates by Raiteri et al. (1993) following the recent analysis by Pignatari et al. (2010), performed with updated cross sections for a solar-metallicity $25M_\odot$ star. The production in stellar winds was then scaled at different metallicities assuming a secondary-like behavior.

Despite the fact that the uncertainties affecting s processing in MS and IMS are very large, they are not critical for our purposes, as their joint contributions to Sr, Y and Zr do not account for more than about 10% of the total solar inventory for these species (Serminato et al. 2009; Bisterzo et al. 2010). Concerning the r-process (or, in general, the primary) components of Sr, Y and Zr, in the presence of huge uncertainties we estimated them to be around 5%. Due to their low values, these rather arbitrary choices are not critical in any respect. Note that Serminato et al. (2009) gave for them values between 5 and 11%.

In order to compute the Galactic chemical evolution of the five observed elements, we proceeded in the following way: i) we derived metallicity-dependent stellar yields for the weak component in massive stars and for the IMS (3-8$M_\odot$). ii) We then assumed that the r-process components of the studied elements are produced at the lowest mass end of type II Supernovae, as in Raiteri et al. (1999) and in Travaglio et al. (1999). iii) With the above ingredients, we followed the chemical evolution of the Galaxy with our model, fixing the uncertain value of the total mass contribution from IMS so that, at the epoch of the Sun's formation and at the corresponding Galacto-centric radius, the sum of all

non-LMS contributions gives the complement to one of our "best average" AGB model (see Subsection 3.3). This means that the percentages form astrophysical sources different from LMS must be of 16% for Y, 20% for Zr, 15% for Ba, 30% for La and 24% for Ce (see also Table 1, column 4, Case C). iv) After this calibration, we introduced the yields of LMS AGB stars, thus computing the total abundance of the studied species as a function of time in the Galactic disk, up to the recent eras when OCs were formed.

With the above assumptions, the Galactic chemical evolution model produces, for the five measured elements, the evolutionary trends shown in Figure 4, where the OC data are shown as empty circles; each of them represents the average of the abundance over all the stars analyzed in the cluster (usually five; for details, see Maiorca et al. 2011). The data for field stars are indicated with crosses of the same size as the errorbar and are taken from the SAGA database. In the left panels, adopting the common way of looking at the chemical evolution of heavy elements, we plotted the observations as a function of the iron abundance or metallicity, [Fe/H], while in the right panels we showed them as a function of time. As already mentioned in Section 1, the plots as a function of metallicity give a confused pattern. This is so because the large scatter in the iron abundances at any given age in the last few Gyr of Galactic life does not make [Fe/H] a good evolutionary indicator for these stages. This finding is in agreement with previous indications by Mashonkina et al. (2007).

Only when the evolution in time is properly reconstructed (right panels) the recent growth of s-elements is unveiled. This is however easily done only for the clusters. Their age is known from a variety of methods: our specific choices, discussed in Paper I, were taken from Magrini et al. (2009). For clusters older than 0.5 Gyr, they made use of the morphological age indicator δV (Phelps et al. 1994), as calibrated by Salaris et al. (2004); for younger clusters they used the most recent age estimates available, like those obtained by the lithium depletion boundary method. For field stars, similar criteria do not exist and

a precise value of their age is usually not available, so that observations referring to them (present in the left panel) cannot be plotted as a function of time.

The s-element abundances in OCs displayed in Figure 4 were measured differentially with respect to the solar photosphere, using the same method of analysis and the same line list (see. Paper I for details). For this reason, the data were normalized to the photospheric solar abundances. These are, in some cases, slightly different from the meteoritic ones (that were used in our "average model" of the solar main component and in deriving the s-process and r-process contributions to the chemical evolution). This explains why, for some elements, the model curves pass above the solar position: it is only an appearance, deriving from the normalization.

In each panel of Figure 4, the shaded areas represent predictions from our calculations and aim at giving an idea of the model sensitivity to the most crucial parameters, i.e. the abundance of ^{13}C burnt and the lower mass limit for TDU operation. The shaded ranges take into account both a variation by $\pm 25\%$ around the average value of our ^{13}C abundance, $X_{13} = (4 \pm 1) \times 10^{-3}$, and the uncertainty on the lowest mass contributing to the process, as discussed in Section 3. In the right panels, two more evolutionary curves are plotted: the long dash-dotted line shows the evolutionary trend obtained by excluding the masses below $1.5 M_\odot$; the short dash-dotted one represents instead a case in which they are included, but using for them the same extension of the ^{13}C pocket adopted for higher mass stars. It should be clear, from the right panels of the figure, that the extra production we assumed from low mass AGB stars offers a means to account for the recent observations of young OCs.

It is relevant to mention that the spectroscopic observations in clusters, which are our original constraints, do not offer us indications with an accuracy better than about $\pm$ 0.1 dex; within these limits we can say that the chemical evolution model, despite

all its uncertainties, suffices to account for the data, namely for a global increase in the abundances that nevertheless maintains a solar-like distribution. This is the main point we want to stress: s-element abundances in Population I stars can be explained, within their uncertainties, by suitably fixing the parameters controlling the neutron source in low mass stars, without the need of further ingredients.

4.2. LMS yields and the solar distribution of heavy elements

As a further test, we ran a few cases in which we included in our Galactic model only the yields of Figures 1 and 3, excluding any further, uncertain contribution from other sources (IMS, MS and the r process). This allowed us to derive an estimate of the role exerted solely by LMS in determining the composition in heavy elements of the recent Galaxy and of the Sun. This role is illustrated in Table 1. There, we put in evidence the uncertainties in the models mentioned before, by showing two possibilities (called cases A and B, presented in columns 2 and 3), where we include (or, respectively, exclude) in the evolutionary calculations the lowest mass bin from 1.25 to $1.3 M_\odot$ (see the discussion in Section 3 for this).

As a comparison, we also show as model C, presented in column 4, the s-process percentages obtained in the yields of our already-mentioned single AGB star, of $1.4-1.45 M_\odot$ and with [Fe/H] $\simeq -0.1$, best approximating the Galactic average and the solar main component.

Despite the necessary cautions related to the models, the exercise shown in Table 1 (cases A and B) makes clear that pure s processing in LMS with a suitable choice of the parameters for the ^{13}C pocket can account for typically 80% (sometimes more) of all the solar s-element abundances. This is so for both ls and hs nuclei, without distinction. As

Table 1

Percentage Contributions to Solar Heavy Elements from LMS

Element	This work (A)	This work (B)	This work (C)	Literature
Strontium	90	89	86	55[1]
Yttrium	81	80	84	62[1]
Zirconium	80	78	80	55[2]
Barium	89	86	85	84[2]
Lanthanum	72	70	70	70[2]
Cerium	79	78	76	81[2]

Cases (A), (B): chemical yields from LMS only, with/without the lowest mass bin

Case (C): composition of the winds of a single AGB star, $1.45 M_\odot$, $[Fe/H] = -0.1$

[1] Travaglio et al. (2004); [2] Bisterzo et al. (2010), single star

Table 2

Percentage contribution to solar s-only nuclei

Isotope	Case A	Case B	Arlandini et al.(1999)
^{100}Ru	95	93	95
^{110}Cd	97	95	97
^{124}Te	94	92	91

a comparison, in Table 1 (column 5) we report the percentages of ls elements attributed to LMS by Travaglio et al. (2004), without the ^{13}C pocket enhancement. These authors underlined that 20-30% of the abundances were not accounted for, even after including the contributions from IMS, massive stars and the r-process. In our new scenario, depicted in Table 1 (columns 2 and 3) the LMS production of the elements considered is increased just by the amount that was missing (20 - 30%), so that the solar abundances of Sr, Y and Zr are now satisfactorily reproduced. We cannot therefore confirm the need, suggested by other authors, for an unknown primary process, sometimes called $LEPP$, or *Lighter Element Primary Process*, contributing to these elements (see e.g Travaglio et al. 2004, for details on this proposal.)

In order to substantiate our statements about s processing, Table 2 reports our LMS

contributions to a few s-only nuclei of the solar distribution with $A < 130$. The results are presented for the cases A and B defined above. Again, considering the 10% errorbar in solar abundances, plus all the model uncertainties, it seems that the solar concentrations of s-only nuclei can be rather satisfactorily explained. In particular, Table 2 shows that our stellar yields, integrated through the chemical evolution model up to the formation of the Sun, can account for essentially the same percentages that could be previously obtained only from average single-star models (see Arlandini et al. 1999).

Note that we consider Tables 1 and 2 only as indications that the solar s-process elements can indeed be explained by pure s-processing. It would be completely outside our scopes to search for a really detailed fit to the solar abundances through a full chemical evolution procedure.

5. Discussion and Conclusions

In the previous sections we presented a tentative interpretation of the increase in heavy element abundances after the Sun's formation, as revealed by recent spectroscopic observations of young open clusters. The increase affects elements that are predominantly produced by slow neutron captures and we showed that their trend in recent stellar systems can be understood as a result of the contributions from very low mass, long-living stars ($M < 1.5M_\odot$, $\tau_{ev} \gtrsim 2$ Gyr), if they activate the main neutron source more effectively than previously suspected.

A consequence of the above suggestion is that also for the Sun the s-process main component can be naturally accounted for, without the need of any extra contribution. An additional conclusion that might be obtained from our procedure concerns the behavior of predominantly-s elements at low metallicity, in comparison to those that are mainly

produced by the r-process, like e.g. Eu. In our cases A and B of Table 1 we found, for the s-process component of Eu, the values of 7.5 and 6.5%, respectively. From this, and making the guess that the complement to one of the abundances for Ba and Eu is due to the r-process, one might deduce a ratio $[\text{Ba/Eu}]_r$ ranging from -0.8 to -0.9. This is roughly compatible with the average values measured in r-process-enriched metal-poor stars, excluding the largely scattered measurements at $[\text{Fe/H}] \lesssim -2.5$ (Suda et al. 2008; Sneden et al. 2008). However, due to the mentioned uncertainties, we believe that such an extrapolation to the r-process is not really robust (although it is usually accepted in the literature). The stellar and Galactic parameters cannot simply be fixed accurately enough to yield a real confidence in such estimates.

Understanding how our scenario is produced is now easy, in the light of the results shown in Figures 1 to 3. What is crucial in this context is the evolution *in time*: most parent AGB stars were born in the last 7.5 Gyr, when the metallicity is high and suitable, with the larger ^{13}C pocket we suggest, to produce *ls* and *hs* elements in similar proportions (similar to those of case C in Table 1).

We notice that, regardless of the specific model we propose here, the same observational data offer a picture of the heavy element evolution in the Galactic disk that is incompatible with the hypothesis that fast primary processes strongly contribute to *ls* elements. Indeed, the fact that the abundances of Y, Zr, Ba, La and Ce grow with respect to iron (and do so very late in the Galactic history) excludes a primary process, the products of which would follow the trend of iron itself. Moreover, the suggestion that a supplementary process modifies selectively the lighter neutron-capture nuclei is contradicted by the fact that in young stellar systems Y and Zr show the same trend as Ba, La and Ce. Furthermore, below $A = 130$ there are a few s-only isotopes, shielded from fast decays, whose production in adequate concentrations requires necessarily the action of slow neutron captures, not of fast

processes.

It is known that the $LEPP$ has been invoked also (and mainly) for extremely metal poor stars. Here the classical idea that fast neutron captures (those of the r process) account for the whole abundances of heavy elements (Truran 1981) was subsequently integrated and modified by new observations (Sneden et al. 2008). First suggestions on the existence of different stellar sites for producing r-process elements of different atomic mass number were advanced from an analysis of the record of live radioactive nuclei in the Early Solar Nebula (Wasserburg et al. 1996). A large observational basis on metal-poor and extremely metal-poor stars now supports the fact that, while above Te-Xe the r-process does appear to be rather universal, the abundances of lower mass elements are more disperse and more difficult to interpret (Aoki et al. 2005; Suda et al. 2008; Roederer et al. 2010). It was noticed that certain heavy nuclei appear to be produced in progenitors forming very little iron (Qian & Wasserburg 2007); it was also suggested that elements at the neutron magic number $N = 50$ might derive from a combination of charged-particle reactions and neutron-captures in high-entropy neutrino winds associated to core-collapse supernovae (Qian & Wasserburg 2007; Wasserburg & Qian 2009; Roederer et al. 2010; Thielemann et al. 2010). It is in any case beyond doubts that lighter and heavier r-process nuclei should come from different sources or from different superpositions of astrophysical conditions (see e.g. Farouqi et al. 2010; Thielemann et al. 2011).

The above confused situation is today the object of a lively debate. Unfortunately, the data and models discussed in this paper cannot offer any clue for the understanding of extremely metal-poor stars. We notice that, also in that case, attempts at explaining the complex observational scenario with suitable combinations of existing mechanisms, without invoking new ad hoc processes, already exist (Qian & Wasserburg 2008; Wasserburg & Qian 2009; Farouqi et al. 2010; Banerjee et al. 2011).

We conclude by mentioning that the extended ^{13}C pocket assumed in this paper would require the existence of very efficient mixing episodes in evolved stars of mass below $1.5 M_\odot$. A similar conclusion was already inferred from very different constraints (Palmerini et al. 2011a,b); in particular, it seems to be necessary for explaining the isotopic admixture of oxygen in presolar oxide grains. The transport mechanisms most commonly-adopted so far (rotationally-driven shear, or thermohaline mixing) would not suffice (Palmerini et al. 2011a). From this point of view, the apparent need of forming extended ^{13}C reservoirs in the short time interval of a TDU episode, might be another indication that other mixing processes must be at play. Phenomena of this kind were recently suggested to be driven by magnetic buoyancy (Busso et al. 2007; Nordhaus et al. 2008); this hypothesis and other mechanisms must now be examined in order to see if it can offer a general interpretation of non-convective mixing in evolved stars.
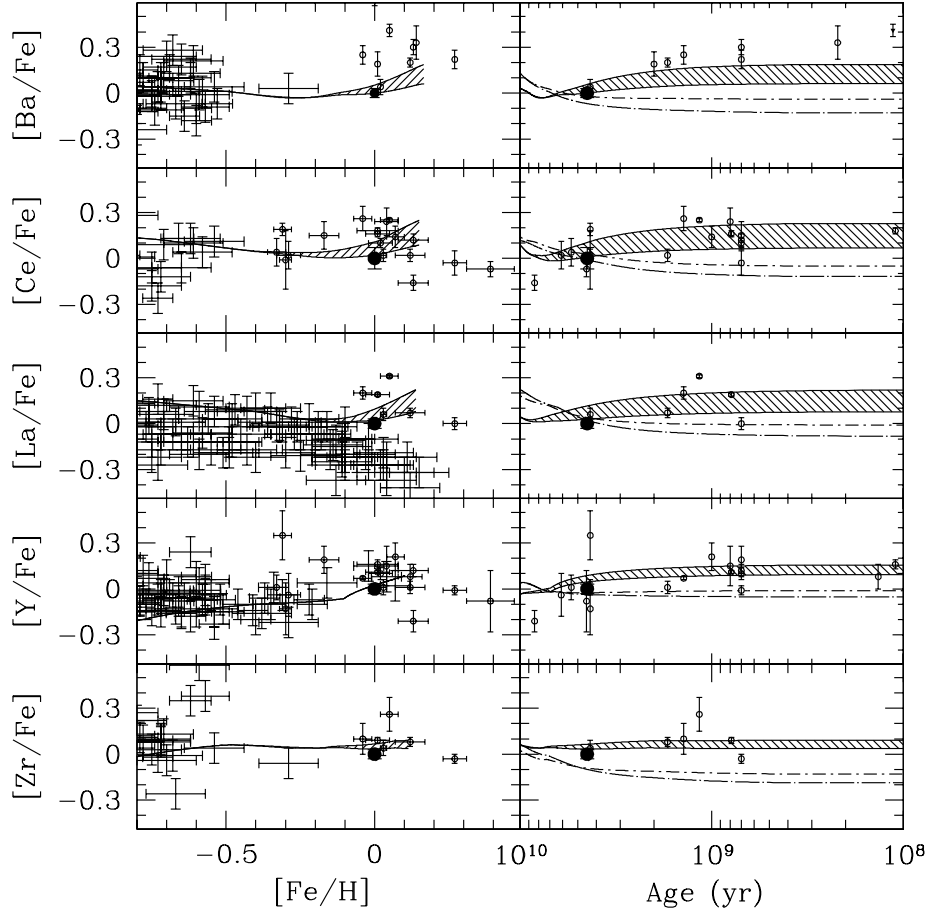
Fig. 4.— The Galactic enrichment in *ls* and *hs* elements from our chemical evolution model, as compared to observed data. The solar photospheric abundances are shown as heavy dots. The left panels show the abundances as a function of [Fe/H]; the data for single stars are from the SAGA database by Suda et al. (2008); their errorbar is not always available, but certainly non-negligible. As an example, the estimates deducted from Table 3 in Simmerer et al. (2004) for La yield an uncertainty of 0.1 dex. Even assuming this value (rather optimistically) as typical for all the measured elements, as done in the plot, we see that the emerging situation is very confused and a definite trend for all the species studied does not emerge. Simply, [Fe/H] is not an adequate parameter to describe the evolution of s elements. The data for OCs are taken from Paper I and from D'Orazi et al. (2009). Each open symbol represents a different cluster; several among them have metallicities higher than solar. In the right panels the abundances are instead plotted as a function of time: here, only the clusters can be displayed (see text). While the data are limited in number, they appear to show clear regularity, without a wide scatter. The shaded area, indicating our model predictions, reproduces the solar and clusters' measurements within the uncertainties of the observations and of the models (see text for explanations). In the right panels, dash-dotted lines show the trends obtained without the extension of the ^{13}C pocket suggested in this paper, either including (short dashes) or excluding (long dashes) masses below $1.5 M_\odot$.

REFERENCES

Abia, C. et al. 2001, ApJ 559, 1117.

Abia, C. et al. 2002, ApJ 579, 817.

Adelberger, E.G., Garcia, A., Robertson, R.G.H. et al. 2011, Rev. Mod. Phys., 83, 195

Anders, E. & Grevesse, N. 1989, Geochim. Cosmochim. Acta 53, 197

Aoki, W. et al. 2005, ApJ 632, 611.

Arlandini, C. et al. 1999, ApJ 525, 886.

Asplund, M., Grevesse, N., Sauval, J, & Scott, P. 2009, ARA&A 47, 481

Banerjee, P., Haxton, W.C., & Qian, Y.-Z. 2011, Phys. Rev. Lett 106, 1104

Bisterzo, S. et al. 2010 MNRAS 404, 1529.

Busso, M., Gallino, R., & Wasserburg, G.J. 1999, ARA&A 37, 231

Busso, M. & Gallino, R. 1985, A&A 151, 205

Busso, M., Picchio, G., Gallino, R., & Chieffi, A. 1988, ApJ 326, 196.

Busso, M., Wasserburg, G.J., Nollett, K.M., & Calandra, A. 2007, ApJ 671, 802.

Busso, M. et al. 2001, ApJ 557, 802.

Cristallo, S. et al. 2009, ApJ 696, 797.

Domínguez, I. et al. 1999, ApJ 524, 226.

D'Orazi, V. et al. 2009, ApJ 693, L31.

Farouqi, K., Kratz, K.L., Pfeiffer, B. et al. 2010, ApJ 712, 1359

Gallino, R. et al., 1998, ApJ 497, 388

Guandalini R., Busso, M., Ciprini, S., Silvestro, G., Persi, P., 2006 A&A 445, 1069G

Guandalini, R. & Busso, M. 2008, A&A 488, 675

Jacobson, H.R., Friel, E.D. & Pilachowski, C.A. 2011, BAAS 43.

Käppeler, F. et al. 1990, ApJ 354, 630.

Käppeler, F., Gallino, R., Bisterzo, S., & Aoki, W. 2011, Rev. Mod. Phys. 83, 157.

Magrini, L., Sestito, P., Randich, S., & Galli, D. 2009, A&A 494, 95.

Maiorca, E. et al. 2011, ApJ 736, 120.

Mashonkina, L.I. & Gehren, T. 2001, A&A 376, 232

Mashonkina, L.I., Vinogradova, A.B., Ptitsyn, D.A. et al. 2007, Astron. Rep. 51, 903

Nordhaus, J. et al. 2008, ApJ 684, L29.

Palmerini, S., La Cognata, M., Cristallo, S., & Busso, M. 2011, ApJ 729, 3.

Palmerini, S., Cristallo, S., Busso, M. et al. 2011, ApJ (in press) [arXiv1107.2844].

Phelps, R.L., Janes, K.A., & Montgomery, K.A. 1994, AJ 107, 1079

Pignatari, M. et al. 2010, ApJ 710, 1557.

Qian, Y.Z., & Wasserburg, G.J. 2007, Phys. Rep. 442, 237.

Qian, Y.Z., & Wasserburg, G.J. 2008, ApJ 687, 272.

Raiteri, C.M. et al. 1993, ApJ 419, 207.

Raiteri, C.M. et al. 2009, ApJ 518, L91.

Roederer, I.U., Cowan, J.J., Karakas, A.I. et al. 2010, ApJ 724, 975

Salaris, M., Weiss, A. & Percival, S.M. 2004, A&A 414, 163

Serminato, A. et al. 2009, PASP 26, 153.

Simmerer J., Sneden C., Cowan J.J., Collier J., Woolf V.M., Lawler J.E., 2004 ApJ 617, 1091

Straniero, O., Domínguez, I., Cristallo, S., & Gallino, R. 2003, PASP 20, 389

Sneden, C., Cowan, J.J., Gallino, R. 2008, ARA&A 46, 241

Straniero, O., Gallino, R., & Cristallo, S. 2006, Nuc. Phys. A777, 311.

Straniero, O., Cristallo, S., Gallino, R. 2009, PASP 26, 133.

Suda, T. et al. 2008, PASJ 60, 1159.

Thielemann, F.-K., Dillmann, I., Farouqi, K., et al. 2010, J. Phys.C 202, 012006

Thielemann, F.-K., Arcones, A., Käppeli, R et al. 2011, Prog. Part. Nucl. Phys 66, 346

Travaglio, C. et al. ApJ 521, 691.

Travaglio, C. et al. 2004, ApJ 601, 864.

Truran, J.W. 1981, A&A 97, 391

Wasserburg, G.J., & Qian, Y.Z. 2009 PASP 26, 184.

Wasserburg, G.J., Busso, M., Gallino, R. 1996, ApJ 466, L109

Wasserburg, G.J., Busso, M., Gallino, R., & Nollett, K.M. 2006, Nuc. Phys. A777, 5.